METHOD OF LASER-RADIATION GUIDING IN PLASMA

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The diffraction broadening of the intense laser radiation restricts its efficient use in many applications. Proposed in the present work is a method for laser radiation guiding in a density channel formed in plasma by a relativistic electron beam. The conditions and parameters of the relativistic beam ensuring the guiding by means of the proposed method have been examined.

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The progress in the technology of high-intensity lasers opens new opportunities for use of lasers in many branches of science and industry. Last years the chirped-pulse amplification technique [1] permitted the production of subpicosecond laser pulses of multiterrawatt power with peak intensity up to $10^{19} W/cm^2$ [2]. With intensities as such we practically have to do with a new interaction range of laser radiation with matter, where the role played by the nonlinear effects is often essential. At present the interactions of high-power laser radiation with plasma are actively investigated in connection with different applications: the excitation of strong plasma wake waves for acceleration of charged particles with acceleration rates to tens of GeV/m [3]; generation, due to nonlinear interaction with plasma, of radiation at harmonics of carrier laser frequency [4]; the "photon acceleration" [5]; X-ray sources [6] etc. Note also such application ranges of laser radiation as the Compton scattering, laser cooling of charged particle beams, the inertial fusion.

The diffraction broadening of laser radiation is one of the principal phenomena (and frequently the primary phenomenon) inhibiting the effective use of the energy of laser in many applications. In vacuum, the laser spot size r_s grows with the longitudinal coordinate according to the formula $r_s = r_0(1 + z^2/Z_R^2)^{1/2}$, where $Z_R = \pi r_0^2/\lambda$ is the Rayleigh length, r_0 is the minimum spot size at the focal point and λ is the laser wavelength. Owing to that, the intensity of radiation quickly decreases as the laser beam propagates. For high-intensity laser pulses the value of Z_R is usually of the order of several millimeters. For instance, in the Laser Wakefield Accelerator (LWFA) scheme the increment in the energy of electrons accelerated by the

longitudinal field of wake wave, excited by a short laser pulse in plasma, is limited by the value $e\pi Z_R E_z$ [3], where E_z is the amplitude of accelerating electric field of the plasma wave, e is the charge of electron. Thus, without optical guiding the diffraction limits the laser-matter interaction distance to a few Rayleigh length.

In a medium, in particular, in plasma, if the index of refraction is maximum at the axis of laser beam and decreases in the radial direction to its periphery, one can eliminate or slow down the process of diffraction broadening of laser radiation (see review in Ref. [7] and numerous references therein). For the laser radiation with power $P > P_c = 2c(e/r_e)^2[\omega/\omega_{pe}(r = 0)]^2 \approx 17[\omega/\omega_{pe}(r = 0)]^2 GW$, where $r_e = e^2/m_e c^2$ is the classical electron radius, ω is the frequency of laser radiation, ω_{pe} is the plasma frequency, there takes place a relativistic self-focusing. However, for short pulses with the length $l \lesssim \pi c/\omega_{pe}$, the relativistic self-focusing proves inefficient for prevention of diffraction broadening [7]. In the experiments the plasma channel is usually formed in the gas or plasma by a laser pulse that, in its turn, is also subject to diffraction. E.g., the parabolic plasma density profile $n_p = n_0 + \Delta n r^2/r_0^2$ may provide the guiding of low-intensity [$a_0^2 = (eE_0/m_e c\omega)^2 \ll 1$, where E_0 is the amplitude of laser radiation] Gaussian laser beam if $\Delta n \geq \Delta n_c = 1/\pi r_e r_0^2 = 1.13 \times 10^{20}/r_0^2[\mu m]\ cm^{-3}$ [7]. The guiding of laser radiation in the preformed plasma density channel at distances from several millimeters to 1-3 cm has been demonstrated by different groups of researchers. In the present work for formation of a plasma channel we propose to use a long relativistic electron beam (REB). REB may traverse, without any essential changes in parameters, the distances in plasma that are much longer than the Rayleigh length of high-intensity laser pulses. The main advantage of the proposed method consists, hence, in the fact that REB can form a plasma channel with lengths much exceeding those obtained in the experiments under survey. So, the method in question could provide longer-term interaction of high-intensity laser radiation with plasma, as well as with relativistic electrons.

Consider the propagation of a cylindrical electron beam with velocity $\mathbf{v}_0 = \mathbf{e}_z v_0$ in cold homogeneous plasma. From the Poisson equation, the equation of motion and the continuity equation for plasma electrons (the plasma ions are taken to be immobile due to their large mass) we have:

$$\frac{\partial^2 \delta n_e}{\partial t^2} + \omega_{pe}^2(\delta n_e + n_b) = 0, \tag{1}$$

where $\delta n_e = n_e - n_0$, n_e is the density of plasma electrons, n_0 is their equilibrium density, n_b is the density of electrons in the beam, $\omega_{pe} = (4\pi n_0 e^2/m_e)^{1/2}$ is the plasma frequency. In case of long beam with the length much exceeding the plasma wavelength $\lambda_p = 2\pi v_0/\omega_{pe}$, and density $n_b = n_b(r)$, one can omit the first term in Eq. (1). Then one has

$$n_e(r) = n_0 - n_b(r). \tag{2}$$

The plasma electrons are blown out of the beam and a density profile (2) is established. Though Eq. (1) was obtained for the linear case when $n_b \ll n_0$, the expression (2) holds true also for $n_b \lesssim n_0$. So, for a function $n_b(r)$ decreasing as r we have a plasma electron density channel. At the same time, the summary density of electrons is constant, $n_e + n_b = n_0 = const$, and is equal to the density of ions, and, therefore, the force acting on the ions of plasma is zero. In this paper we shall show that in spite of the summary density of electrons during the traversal of long electron beam through plasma is constant, the guiding of laser radiation in this case is possible. The problem of the formation of plasma channel and the stability of electron beam will be discussed below.

For consideration of the problem of laser radiation guiding in the plasma density channel with density (2), first examine the dispersion properties of electromagnetic (EM) waves in the channel. From the Maxwell equations one can has for the electric field strength of EM wave

$$rotrot\mathbf{E} = \boldsymbol{\nabla}(\boldsymbol{\nabla}\mathbf{E}) - \Delta\mathbf{E} = -\,c^{-2}(\partial^2\mathbf{E}/\partial t^2 + 4\pi\partial\mathbf{j}/\partial t), \tag{3}$$

where $\mathbf{j} = -e(n_e\mathbf{v}_e + n_b\mathbf{v}_b)$ is the density of current, $\mathbf{v}_e$, $\mathbf{v}_b$ are the velocities of plasma electrons and beam respectively. For a linearly polarized wave, $\mathbf{E} = \mathbf{e}_x E_x = \mathbf{e}_x E_0 \exp[i(\omega t - kz)]$, $\mathbf{B} = \mathbf{e}_y(ck/\omega)E_x$, where $\mathbf{B}$ is the vector of magnetic induction, we obtain from (3)

$$(k^2c^2 - \omega^2)E_x = 4\pi e[n_e(r)\partial v_{ex}/\partial t + n_b(r)\partial v_{bx}/\partial t]. \tag{4}$$

On obtaining the expression (4) we assumed that the response of plasma channel to the propagation of the laser radiation is linear, hence the change of n_e and n_b under action of EM wave is negligible (that is, nonlinear terms $v_{ex}\partial n_e/\partial t$ and $v_{bx}\partial n_b/\partial t$ are threw away). This takes place when $a_0^2 = (eE_0/m_e c\omega)^2 \ll 1$ [3]. To be exact, in our case Eq. (4) is valid if the change in the density of plasma electrons under the action of EM wave, that

is proportional to a_0^2, is much less than the change of density under the action of electron beam, i. e. , $a_0^2 \ll n_b/n_0$. The derivatives of velocities v_{ex} and v_{bx} in the right hand side of Eq. (4) will be obtained from the equations of motion:

$$\frac{\partial v_{ex}}{\partial t} = -\frac{e}{m_e} E_x, \tag{5.1}$$

$$(\frac{\partial}{\partial t} + v_{bz}\frac{\partial}{\partial z})(v_{bx}\gamma_b) = -\frac{e}{m_e}(E_x + \frac{v_{bz}}{c} B_y), \tag{5.2}$$

where $\gamma_b = (1 - \mathbf{v}_b^2/c^2)^{-1/2}$ is a relativistic factor. In case of relativistic electron beam, when $\gamma_0 = (1-v_0^2/c^2)^{-1/2} \gg 1$, we can put $v_{bx} \ll v_{bz} \approx v_0 \approx c$. Taking into account that $\gamma_0^2 v_{bx}^2/c^2 = (eE_x/m_e c\omega)^2 = a^2 \ll 1$, we obtain from (5.2) $\partial v_{bx}/\partial t = -(e/m_e\gamma_0)E_x$. Substituting this expression and Eq. (5.1) into Eq. (4) and taking into account (2) we obtain the following dispersion relation

$$\omega^2 = k^2c^2 + \omega_{pe}^2[1 - \alpha(1 - \gamma_0^{-1})] \approx k^2c^2 + \omega_{pe}^2(1 - \alpha), \tag{6}$$

where $\alpha = n_b(r)/n_0$. In the absence of beam ($\alpha = 0$) one has from (6) an ordinary dispersion relation for transverse waves in cold homogeneous plasma. The expression (6) is valid also for the case of a circularly polarized wave, because one can write that as a superposition of two linearly polarized waves. So, although the summary density of electrons $n_b + n_e = const$, EM wave does not "feel" the relativistic electron beam owing to the fact that the relativistic mass of beam electrons is much larger than the mass of plasma electrons, just as the ions make negligible contribution to the dispersion relation thanks to their large mass. For this reason, instead of REB one can use a beam of relativistic or nonrelativistic negatively charged ions. It is noteworthy also that instead of a continuous beam one can use a long succession of bunches, the separation between which is much less than the plasma wavelength. EM wave can propagate both along and opposite REB. The latter is important for such applications as Compton scattering or a plasma-based free electron laser [8].

From Eq. (6) we have for the index of refraction $N = ck/\omega$ of EM wave (laser radiation)

$$N^2 = 1 - [1 - \alpha(r)]\omega_{pe}^2/\omega^2. \tag{7}$$

The guiding of laser radiation is possible when the condition $dN/dr = (\omega_{pe}^2/2N\omega^2)d\alpha/dr < 0$ is observed. Consider now a parabolic profile of the electron beam density, $\alpha = \alpha_0(1 - r^2/r_b^2)$, $r < r_b$, and the Gaussian profile of the laser radiation, $a = (a_0 r_0/r_s)\exp(-r^2/r_s^2)$. Then $n_e(r) = n_e(0) + n_b(0)r^2/r_b^2$, where $n_e(0) = n_0 - n_b(0)$. In this case the plasma electron density channel produced by REB provides the laser radiation guiding when (see Chapter VI in Ref. [7])

$$n_b(0) > \Delta n_c (r_b r_0)^2/r_s^4. \tag{8}$$

For instance, when $r_b = r_s = 2r_0$ and $r_0 = 500\mu m$,we have $n_b(0) > 1.13 \times 10^{14} cm^{-3}$, and the Rayleigh length is $Z_R \approx 7.85 cm$ for the wavelength of laser radiation $\lambda = 10\mu m$.

The linear case ($\delta n_e \ll n_0$) considered above was when $a_0^2 \ll \alpha_0 \ll 1$. At the violation of this condition the mathematical description of the problem is complicated, but the guiding again is possible. Moreover, one can weaken the condition of guidance. In case when $a_0^2 \gtrsim \alpha_0$, one can weaken the condition of guidance (8) for the long laser beam ($l \gg \lambda_p$), first, because of the fact that the plasma electrons are blown out of the channel by the laser radiation owing to which the effect of guiding is amplified, and, second, due to the effect of relativistic self-focusing. When $a_0^2 \ll 1$, the condition of laser radiation guiding in this case takes on the form (see Ref. [7]):

$$\frac{P}{P_c} + \frac{a_0^2}{2}\frac{r_0^2}{r_s^2} + \frac{n_b(0)}{\Delta n_c}\frac{r_s^4}{(r_b r_0)^2} > 1.$$

The large gradient of plasma density in the channel may be formed by a dense REB when $n_b \gtrsim n_0$. In this case there is formed a range close to the beam axis, where all plasma electrons are driven out. For a thin beam (with the radius $r_b \ll \lambda_p$) such a range is formed when $n_b > n_0$, and for a broad beam ($r_b \gg \lambda_p$) - when $n_b > n_0/2$, the diameter of range increasing with the beam density [9].

Now consider the problems of plasma channel formation and the plasma stability. To avoid the excitation of plasma wave by the leading edge of electron beam, the density of REB at the entry into plasma should grow rather slowly, to wit as $t_b \gg \omega_{pe}^{-1}$ where t_b is the rise time of beam density. However, for applications connected with the acceleration of charged particles the excitation of plasma wave by the electron beam may prove desirable. During the flight of REB through plasma it is subject to different forms of

instability. The condition of neglect of an instability may be written in the form $\delta\Delta t \lesssim 1$, where δ is an increment of the instability and Δt is the time of flight of electron beam through plasma; for relativistic beam $\Delta t \approx l\,/c$, where l is the length of plasma column. The most quickly developing instability is the beam-plasma instability as a result of which a plasma wave with wave number $k \approx \omega_{pe}/v_0$ is excited. The development of beam-plasma instability leads eventually to a breakage of beam into bunches flying with the period of plasma wave. The increment of beam-plasma instability for waves propagating along the direction of electron beam flight (i.e., along z axis) is (see, e.g., Ref. [10])

$$\delta = (3^{1/2}/2^{4/3})\omega_{pe}(n_b/n_0)^{1/3}/\gamma_0. \tag{9}$$

It follows from (9) that the increment of beam-plasma instability decreases with increasing energy of beam electrons, i.e., for sufficiently large γ_0 one can neglect the instability. According to (9), one can neglect the instability for

$$\gamma_0 \gtrsim 1.3 \times 10^{-6} n_0^{1/2}[cm^{-3}](n_b/n_0)^{1/3} l[cm].$$

For $n_0 = 10^{14} cm^{-3}$, $n_b/n_0 = 0.1$ and $l = 50cm$, one has $\gamma_0 \gtrsim 300$. The development of beam-plasma instability may be desirable for a number of applications, e.g., for generation of picosecond and femtosecond electron bunches. In this case the wake wave excited by a short laser pulse in the plasma channel produced by the electron beam would enable one to control the beam instability.

Consider the problem of guiding from an energetic point of view. The energy density of REB and laser beam are respectively $W_{REB} = m_e c^2 \gamma_0 n_b$ and $W_{Las} = E_0^2/8\pi = (m_e c\omega/e)^2 a_0^2/8\pi$, and for their ratio one has

$$\kappa \equiv \frac{W_{REB}}{W_{Las}} = \frac{2\gamma_0(n_b/n_0)}{a_0^2}\left(\frac{\lambda}{\lambda_p}\right)^2. \tag{10}$$

The wavelength λ of modern high-intensity lasers is in order of several micrometer (the value of $\lambda \approx 1\mu m$ is typical for a solid state laser and $\lambda \approx 10\mu m$ for the CO_2 laser). In the case $n_0 = 10^{14} cm^{-3}$, $n_b/n_0 = 0.1$, $\gamma_0 = 300$, $\lambda = 1\mu m$, and $a_0^2 = 0.05$ (that corresponds to the circularly polarized laser beam intensity $I \approx 1.4 \times 10^{17} W/cm^2$) from expression (10) follows $\kappa \approx 1.08 \times 10^{-4}$. When $n_0 = 10^{16} cm^{-3}$, $n_b/n_0 = 0.1$, $\gamma_0 = 100$, $\lambda = 10\mu m$, and $a_0^2 = 0.1$ ($I \approx 2.8 \times 10^{15} W/cm^2$) one has $\kappa \approx 0.18$. Thus, REB allows to

guide laser radiation with the energy density much exceeding that of REB. The total energy of REB $\varepsilon_{REB} \sim \pi r_b^2 l_{REB} W_{REB}$, for practically interesting parameters of the problem, can be more or less than the total energy of laser beam $\varepsilon_{REB} \sim \pi r_0^2 l_{Las} W_{Las}$; here l_{REB} and l_{Las} are respectively the length of REB and laser beam.

It was shown above that the relativistic electron beam can form a channel in plasma, in which the laser radiation guiding is possible. The proposed guiding method is based on the capacity of relativistic electron beam to traverse, without essential change in parameters, the distances in plasma much larger than the diffraction length of high-intensity laser radiation. The plasma electrons are blown out of the range occupied by REB, as a result of which a plasma channel is formed in plasma, the density in which increases in radial direction. It was shown that owing to large relativistic factor of REB, its contribution to the dispersion properties of channel is negligible. The method under consideration permits an essential increase in the interaction time of laser radiation with plasma and electron beam and, hence, in the efficiency of using the radiation energy.

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REFERENCES

[1] D. Strickland and G. Mourou, Opt. Commun., **56**, 219 (1985).

[2] M. D. Perry, In: *Advanced accelerator concepts,* edited by P. Schoessow, AIP Conference Proceedings No. 335, 1995.

[3] E. Esarey, P. Sprangle, J. Krall, and A. Ting, IEEE Trans. Plasma Sci. **24**, 252 (1996).

[4] P. Sprangle, E. Esarey, and A. Ting, Phys. Rev. A **41**, 4463 (1990).

[5] S. C. Wilks, J. M. Dawson, W. B. Mori, T. Katsouleas, and M. E. Jones, Phys. Rev. Lett. **62**, 2600 (1989).

[6] N. H. Burnett and P. B. Corkum, J. Opt. Soc. Am. B, **6**, 1195 (1989).

[7] E. Esarey, P. Sprangle, J. Krall, and A. Ting, IEEE J. Quantum Electron., **33**, 1879 (1997).

[8] K. Nakajima, M. Kando, T. Kawakubo, T. Nakanishi, and A. Ogata, Nucl. Instr. and Meth. A **375**, 575 (1996).

[9] I. A. Kotel'nikov and V. N. Khudik, Fizika Plazmy, **23,** 146 (1997) [Plasma Phys. Rep., **23**, 130 (1997)].

[10] A. B. Mikhailovskii, *Theory of Plasma Instabilities* (Consultants Bureau, New York, 1974), Vol. I.